implant thickness. Based on (3), (4), and the material velocities listed in Table I, we can position the IB sufficiently close to the target range for all four materials using a thickness of 1.5 mm. Table II shows the calculated 1-D resonance frequencies for different materials. Receivers made from PZT4 and PZT5H have lower resonance frequencies than those made from $BaTiO_3$ and $LiNbO_3$ due to lower sound velocity.

TABLE II

Calculated resonance and impedance assuming

	PZT4	PZT5H	$BaTiO_3$	$LiNbO_3$
f_{sc} (MHz)	1.06	0.95	1.49	1.90
R_{sc} (kΩ)	2.48	1.15	1.94	82.5
f_{oc} (MHz)	1.37	1.28	1.67	2.13
R_{oc} (kΩ)	244	119	56.6	2612

t=1.5 mm, w=1.1 mm, Z_F=1.5 MRayls and Z_B~0 MRayls.

[0072] The area of the ultrasonic receiver and piezoelectric materials offers another trade-off between implant size and power capture area. As an example demonstration, we choose a lateral dimension, w, of 1.1 mm and use material as a design parameter to achieve the desired impedance range. Shown in FIG. **9**, the off-resonance resistance in the IB is bounded by short circuit resistance, R_{sc}, and open circuit resistance, R_{oc}. Using the chosen dimensions, acoustic loadings, and the material properties in Table I, R_{sc} and R_{oc} can be calculated with the following equations derived from the series circuit model,

$$R_{sc} \cong \frac{1}{8k_{33}^2 f_{sc} C_0} \frac{Z_F + Z_B}{Z_c} \propto \frac{1}{\rho v^2 \varepsilon^T k_{33}^2 (1 - k_{33}^2)^{\frac{3}{2}}} \frac{t^2}{w^2} \tag{5}$$

$$R_{sc} \cong \frac{2k_{33}^2 f_{sc}}{\pi^2 f_{oc}^2 C_0} \frac{Z_c}{Z_F + Z_B} \propto \frac{\rho k_{33}^2}{\varepsilon^T (1 - k_{33}^2)^{\frac{1}{2}}} \frac{t^2}{w^2}. \tag{6}$$

Equations (5) and (6) also show the direct relationship of R_{sc} and R_{oc} to the material properties under the assumption of given acoustic loadings (i.e. tissue and air for front and backing loading respectively). The calculated values for a thickness of 1.5 mm and width of 1.1 mm are shown in Table II. R_{sc} and R_{oc} are similar for receivers made from PZT4, PZT5H, and $BaTiO_3$; in addition, these materials offer an off-resonance resistance range that is well-matched to the desired R_{in} from Section B2. Conversely, the resistances for receivers made from $LiNbO_3$ are nearly two orders of magnitude higher due to drastically lower relative permittivity as captured by (5) and (6). Although increasing the area of the piezoelectric receivers can be used to lower impedance range, this is undesirable for the purpose of miniaturization. Therefore, $LiNbO_3$ is not a preferred material for mm-sized implants of the specific targeted power range in this work, while PZT4, PZT5H, and $BaTiO_3$ are well-suited for our applications.

[0073] The above arguments are not meant to be a comprehensive analysis of all piezoelectric materials and sizing, but are provided to demonstrate various tradeoffs given a target power level and volume. Depending on the requirements of the application, a similar analysis can be carried out to investigate the feasibility of different materials and dimensions. For example, with the given dimensions, single crystalline piezoelectric materials such as PMN-PT (Lead Magnesium Niobate-Lead Titanate) are more suitable for applications requiring a higher power range (>1 mW) due to their large $\in^T$ (~5000) and k_{33} (~0.9). One can also tune the properties of the piezoelectric materials by utilizing a composite piezoelectric transducer. Additionally, for shallow IMDs (<5 cm), a shorter link reduces the acoustic loss through tissue, and thus, higher frequency operation can be used to further scale down the thickness and width of the receiver while maintaining the desired impedance range.

B4) Characterization of Receivers

[0074] Ultrasonic receivers were built using PZT4, PZT5H, and $BaTiO_3$ to compare the general impedance behavior with the first-order analysis. We also measured acoustic-to-electrical power conversion efficiency, PCE, across the IB for each material. The PCE is defined mathematically as,

$$PCE = \frac{P_{av,ele}}{P_{acou}} = \frac{P_{av,ele}}{I_0 A}, \tag{7}$$

where $P_{av,\,ele}$ is the available electrical power and P_{acou} is the incident acoustic power, which is the product of incident acoustic intensity on top of the receiver characterized by a hydrophone, I_0, and physical area of the receiver, A. PCE is the acoustic-to-electrical efficiency analogue of aperture efficiency of an antenna. It varies across frequency and does not depend on electrical loading or characteristics of the ultrasonic transmitter so long as the receiver is in the far-field.

[0075] All piezoelectric receivers have a thickness of 1.5 mm, were diced to a width of 1.1 mm, and were packaged on top of a printed circuit board (PCB). We designed the package to minimize the total volume of the device. A bond wire and copper sheet were used to establish top and bottom electrical connections to receivers' electrodes. Air backing was created by sealing the via hole on the PCB. FIG. **11** shows the diagram and the photo of the package. Here **1102** is the piezoelectric receiver, **1104** is the copper sheet, and **1106** is the printed circuit board.

[0076] The receiver was immersed in a custom tank filled with mineral oil (1.16 MRayls) in order to minimize electrical parasitics and mimic the acoustic loading of body tissue. The ultrasonic transmitter (Olympus A303S) and the receiver were spaced at a distance of 6.0 cm to ensure both devices are in the far-field region. In practice, one would use a focusing array to get higher link efficiency, but here we are only interested in characterizing the ultrasonic receivers, independent of the transmitter.

B4a) Measured Resonances and Impedances of Receivers

[0077] We characterized the impedance profile of the ultrasonic receivers using an impedance analyzer (Agilent 4294A). FIGS. **12**A-C show the measured and calculated R_{piezo} from the series circuit model with a correction factor of 0.93 (for G ~0.7) to correct resonance frequency. The values of the resonance frequencies, R_{sc}, and R_{oc} are listed in Table III. We omit the reactance across the IB since we can utilize a capacitor-only matching network to cancel the reactance as described in section B5. The measured R_{piezo}